Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24**, 93–109 (1999)

LATEGLACIAL RIVER SEDIMENT BUDGETS IN THE MAAS VALLEY, THE NETHERLANDS

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Received 31 July 1997; Revised 2 July 1998; Accepted 10 July 1998

ABSTRACT

Three Weichselian Lateglacial (13–10 ka) terraces have been distinguished in the Maas valley which were formed when the Maas repeatedly incised in an increasingly narrow floodplain. The River Maas changed from a braided system (before *c.* 12·5 ka) via a transitional phase to a high-sinuosity meandering river (*c.* 12·5–11 ka), to a braided system (*c.* 11–10 ka) again and finally to a low-sinuosity meandering river (after 10 ka). These fluvial style changes involved phases of erosion and deposition. The amounts of eroded, deposited and reworked sediment during each Lateglacial period are calculated in this paper. The sediment budgets allow comparison of the transport capacity of the different river styles, which will help to explain the observed fluvial changes. Borehole information regarding the thickness of terrace sediments and lateral extensions of the Lateglacial terrace surfaces were combined in a three-dimensional approach, using a geographical information system. Multiple regression analyses were used in calculating altitudes of entire terrace surfaces from individual altitude measurements. It will be shown that the fluvial development of the Maas can be explained not only by climate-related external factors such as sediment–discharge ratios and discharge characteristics, but possibly also by intrinsic factors such as floodplain dimensions and the channel morphology of previous periods. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS weichselian; sediment budgets; GIS; fluvial style changes; climate change

INTRODUCTION

This paper aims to explain the complex nature and causes of fluvial responses to climate change by calculating amounts of eroded, reworked and deposited sediment by different river types during Lateglacial warm and cold periods. The Maas changed from a braided river in the Late Pleniglacial via a transitional phase into a meandering river in the Allerød, it became braided in the Younger Dryas and meandering in the Holocene (Bohncke *et al.* 1993; Vandenberghe *et al.* 1994; Kasse *et al.* 1995; Huisink 1997). Incision and terrace formation took place at climatic transitions, from a warm to cold period (Allerød to Younger Dryas) and cold to warm periods (Pleniglacial to Bølling, Younger Dryas to Holocene), whereby the Maas became confined in an increasingly narrow floodplain. The study reach of the Maas valley (Figure 1) comprises the most complete Lateglacial terrace sequence and is located just upstream of the intersection of Weichselian and Holocene deposits.

The Lateglacial (13–10 ka) was a period of large climatic changes in north western Europe (Bohncke and Wijmstra 1988; Van Geel *et al.* 1989; Walker *et al.* 1994; Paus, 1995; Hoek, 1997; Isarin 1997). Figure 2 shows mean annual and July temperatures for the Lateglacial and the division in the Bølling–Allerød interstadial and Younger Dryas stadial, which is commonly used in The Netherlands. The Pleniglacial represents the middle part of the last glacial of which the Late Pleniglacial (*c.* 27–13 ka) was the period of maximum cold. The impact of these climatic changes on lowland rivers in north western Europe is recognized in many river valleys (e.g. Kozarski, 1983; Schirmer, 1983; Rose, 1995; Kalicki and Zernickaya, 1995; Antoine, 1997). The Maas valley in particular, being one of the largest rivers of The Netherlands, has been intensively studied by Pons and Schelling (1951), Van den Broek and Maarleveld (1963), Bohncke *et al.* (1993), Vandenberghe *et al.* (1994), Berendsen et al. (1995), Kasse *et al.* (1995),

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Contract/grant spnsor: NWO, Dutch Organization for Scientific Research

CCC 0197-9337/99/020093–17 $17.50

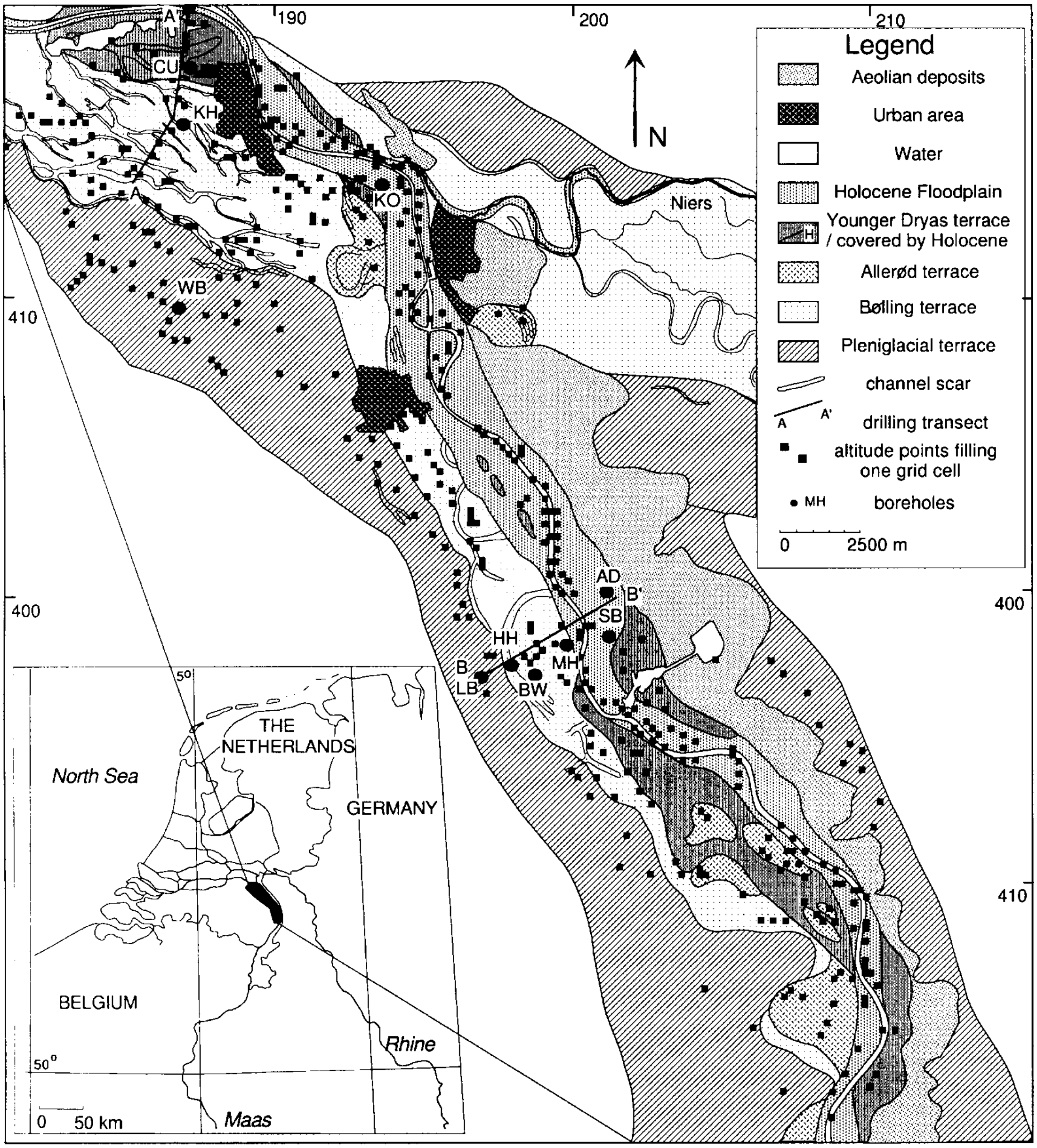

Figure 1. Location of study area and Lateglacial terraces

Van den Berg (1994, 1996) and Huisink (1997, 1998).

The River Maas drains an area of 33 000 km^2; it is rainfed and discharges range from 300 m^3 s^{-1} in summer to 3000 m^3 s^{-1} in winter. Fluvial style changes of the Maas during the Lateglacial are most probably related to the distinct climatic changes in that period. The occurrence of tectonic activity did not account for the observed fluvial changes, although it influenced the formation and preservation of terraces in the Maas valley (Huisink, 1998). The hinterland of the Maas, the Ardennes, has been subjected to a gradual uplift from the Miocene onwards with periods of accelerated tectonic activity superimposed on a general continuous trend (Van den Berg, 1994). The long-term uplift of the Ardennes cannot explain the formation of three terraces in 3000 years however. Lateglacial tectonic activity in the Venlo Graben, in which the study reach is located, is shown by steepening of the longitudinal profiles of

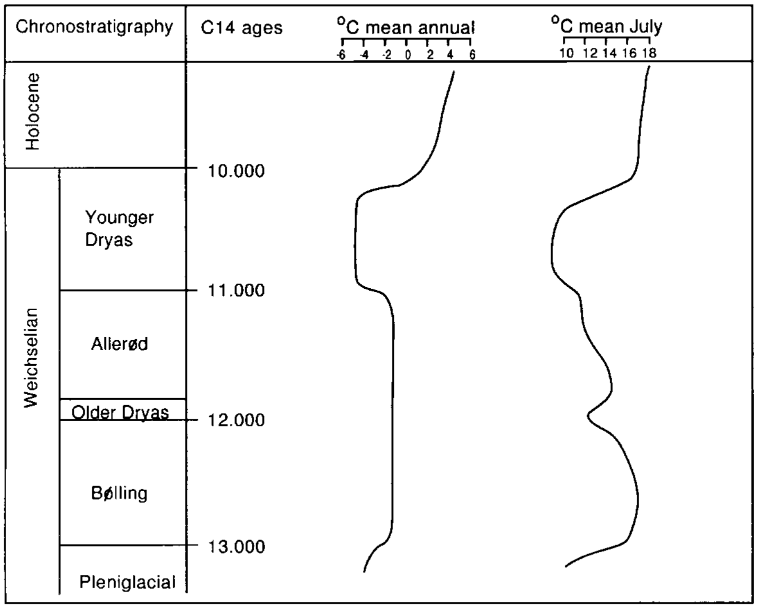

Figure 2. Chronostratigraphy and temperatures in the Weichselian lateglacial. Mean July temperature after Walker *et al.*. (1994); mean annual temperature after Kasse *et al.* (1995)

parts of the Pleniglacial and Bølling terraces, but it did not trigger fluvial changes (Huisink, 1998). The braided (late Pleniglacial) and transitional (Bølling) river systems could be traced along large parts of the valley without changes in morphology or sedimentology, regardless of (tectonically induced) locally steeper slopes. The meandering Allerød river and the braided Younger Dryas river had different river styles but similar floodplain gradients (23·5 and 25·1 cm km^{-1}, respectively) which shows that floodplain gradients were not determining the fluvial style. Sea level was not an important control since it was some 100 m lower in the Lateglacial (Jelgersma 1966) and the study area was at 400 to 500 km distance from the coastline at that time.

Since the terrace extensions are known and mechanically drilled boreholes provide information about sediment thickness, it is possible to quantify the erosion, deposition and reworking of the Lateglacial River Maas. Quantitative fluvial studies often deal with short time-scales and site-specific river reaches where a lot of data are gathered (e.g. Lane and Richards, 1997), or with modelling of large areas over long time periods where limited detailed data are available (e.g. Veldkamp and Van den Berg, 1993). Quantification of erosional and depositional phases during the last glacial usually involve one-dimensional estimates of depths of incision or deposition from particular sites. By using a geographical information system (GIS), a three-dimensional approach is possible in a valley stretch. The GIS enables calculations to be made and shows the geographical variation within the study area, as the fluvial processes of erosion and sedimentation change from up- to downstream parts of the valley. The distinction between the terraces and the sedimentology of the sediment facies has been described previously by Huisink (1997). New data from deeper boreholes are used to determine the thickness of sediment units.

THE LATEGLACIAL TERRACE STRATIGRAPHY

One late Pleniglacial (*c.* 27–13 ka) and three Lateglacial terrace surfaces have been recognized (Huisink, 1997). Sediment characteristics and channel morphology on the terrace surfaces enabled an interpretation of changing river styles. The oldest sediments in this study are deposited by a braided river in the cold Pleniglacial. The river occupied a large floodplain, bounded by higher relief in the west

(Peelhorst) and remnants of older Rhine terraces in the east. The braided river system developed during the warmer Bølling period into a transitional style between braiding and meandering and the floodplain width decreased. Minor channels were abandoned, while larger ones started to incise, formed levees and deposited overbank sediments. The incision trend of major channels and abandonment of smaller ones continued until finally a single meandering channel remained active in the Allerød (12–11 ka, Figure 2). This channel was confined to a rather narrow floodplain in which it moved laterally. At the onset of the cold Younger Dryas (11 ka, Figure 2) the river incised significantly and changed abruptly to a braided river system. The river filled the incision only partially. New incision took place at the start of the Holocene and the Maas became meandering again. During the Holocene the river deposited mostly fine-grained sediments.

CREATION OF TERRACE AND ALTITUDE MAPS USING A GIS

Figure 1 shows the extent of the terraces in the study area which is used as a base for the creation of GIS maps in PCRaster (Wesseling *et al.* 1996). This part of the Maas valley was divided into grid cells of 200 by 200 m, which allows an acceptable representation of the Maas valley. For each grid cell x- and y-coordinates, terrace code and altitude are given.

Altitudinal points (minimum of 54 and maximum of 133) on each terrace surface were obtained from 1:10 000 altitude maps. These points (Figure 1) were carefully selected from the highest parts of the terrace surfaces, mostly the top of point bar sediments or levees (Huisink, 1998) and used in multiple linear regression analyses to obtain the terrace altitudes in the whole valley reach. The output of the multiple linear regression analyses is an equation for each terrace, that represents the best fit of a surface through the observed altitude points. These equations enable the altitude of each grid cell in the Maas valley to be calculated. The accuracy of the multiple linear regression analyses proved to be high as the R^2 value varied from 0·92 to 0·98 (Huisink, 1998). GIS maps of the present River Maas valley are presented in Figure 3, showing the terrace code in each grid cell (Figure 3a) and the calculated altitude (Figure 3b).

MAXIMUM AND MINIMUM TERRACE DIMENSIONS

PCRaster is used to calculate palaeofloodplain surfaces in the late Pleniglacial and Lateglacial before erosion or incision by adding subsequently incised terraces. The surface of former floodplains is difficult to establish when remnants of younger terrace surfaces are scattered or located on only one side of the river. In the latter case the range between maximum and minimum extensions of palaeoterrace surfaces is calculated.

Pleniglacial floodplain dimensions

As the Pleniglacial terrace surface is found on both sides of the River Maas (Figure 1), the Pleniglacial river must have occupied all the intermediate area as well (Figure 4A).

Bølling floodplain dimensions

The Bølling terrace is found only on the west side of the River Maas. The maximum floodplain area is the combination of the Bølling terrace surface with all younger terrace surfaces (Figure 4B). A calculation of the minimum Bølling floodplain area is the sum of the terrace remnants that are actually found in the valley (Figure 4C), which is not the most probable assumption since incision of this terrace took place in the Allerød (Huisink, 1997; Kasse *et al.,* 1995). The average of the minimum and maximum calculated floodplain sizes is in this case more realistic.

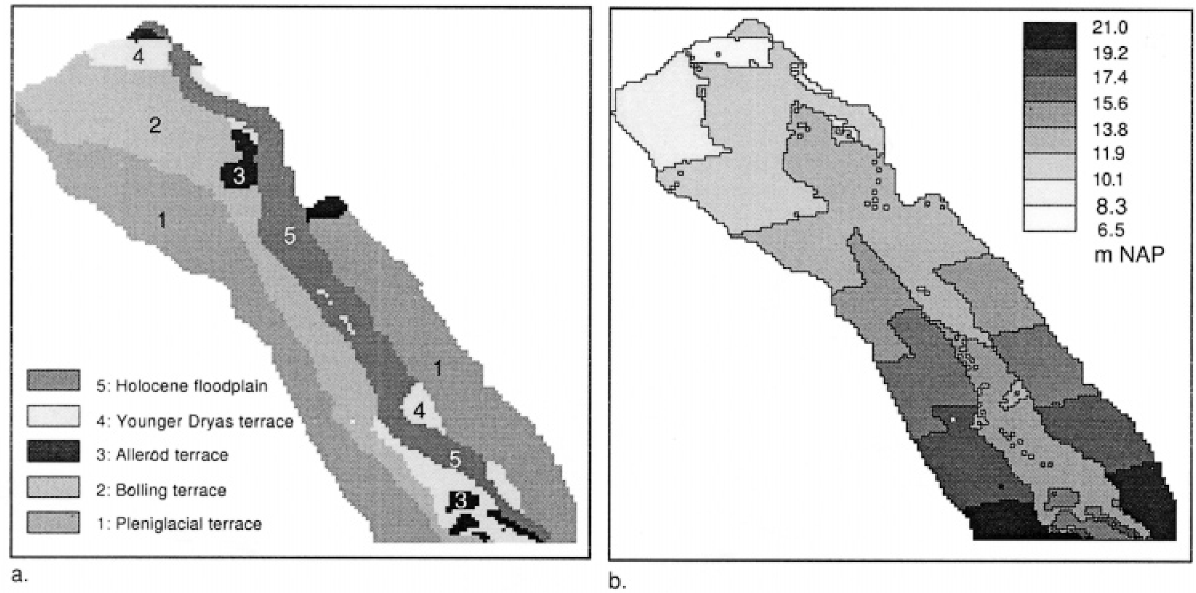

Figure 3(a) Lateglacial GIS terrace map (based on Figure 1). (b) Maas valley altitude map

Allerød floodplain dimensions

The reconstruction of the Allerød palaeofloodplain dimension is difficult since terrace fragments are scarce. Most of the terrace surface was destroyed by erosion during the Younger Dryas and Holocene. A maximum floodplain area is the sum of the AllerdAllerød and Younger Dryas terrace surfaces and the Holocene floodplain (Figure 4D). A minimum estimation of the Allerød floodplain area, based on present-day terrace remnants only, has not been made because the Allerød terrace fragments do not form a continuous floodplain (Figure 1). A better estimate of the minimum floodplain size of the Allerød meandering river can be obtained by comparison with the actual, also meandering river floodplain, since the size of the Allerød meander scars is comparable with meanders in the Holocene floodplain (Figure 1).

Younger Dryas floodplain dimensions

Most of the Younger Dryas terrace sediments have been eroded in the Holocene, but Younger Dryas terrace remnants are found on both sides of the Holocene floodplain (Figure 1). The maximum terrace surface is therefore obtained by adding the Younger Dryas and Holocene floodplain dimensions (Figure 4E). The minimum floodplain size cannot be obtained because the Younger Dryas terrace is found as fragments only and the terrace surface is covered by Holocene deposits in the northern part of this study area. The maximum extension of the Younger Dryas floodplain is the most accurate reconstruction possible and is therefore used in this study.

THICKNESS OF SEDIMENT BODIES

The late Pleniglacial and Lateglacial terrace sediments consist mostly of coarse sand and gravel and are described in detail by Huisink (1997). Table I shows a summary of sediment characteristics which have been used to differentiate Lateglacial terrace sediments from older deposits and to estimate terrace sediment thickness. Most boreholes in this area have been made by hand and did not penetrate the basal gravels of the terrace sediments (Huisink, 1997), so mechanical boreholes were used that penetrated deeper and provided undisturbed samples. Six boreholes were located in the southern part of the study

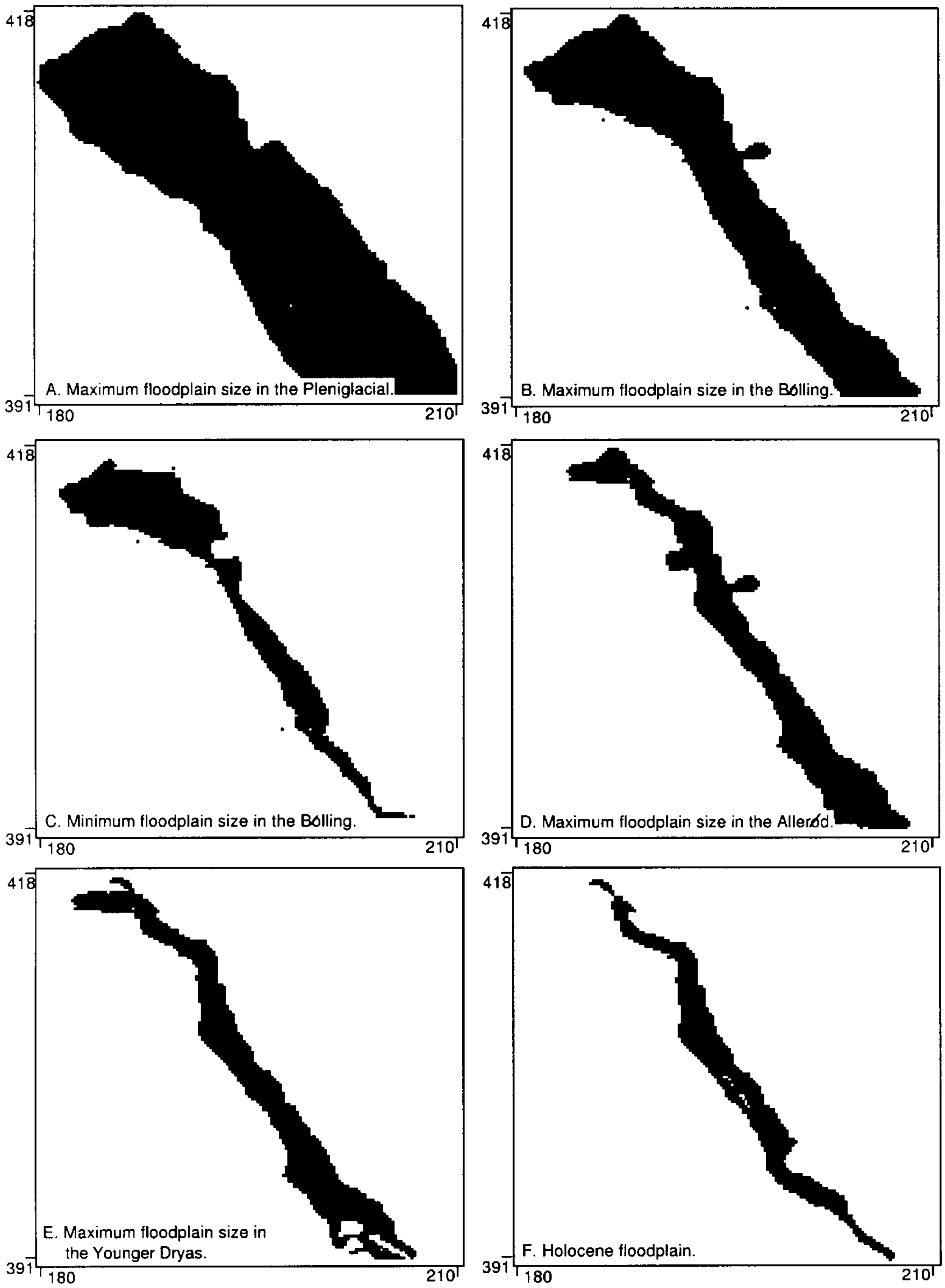

Figure 4. Lateglacial floodplain dimensions

Table I. Sediment charactristics of the Maas terraces

Terrace	Sediment characteristics	Length of fining-up sequences
Holocene floodplain	Mostly fine-grained, sometimes clayey sand, silt and organic material, lowermost sediments are coarse	
Younger Dryas	Coarse-grained, poorly sorted, gravelly sand, abrupt lithological changes, both laterally and horizontally	1–2 m
Allerød	Channel fill: peat and gyttja, fine-grained, rather well sorted, silty sands at the top of a fining-up sequence, changing downwards into coarse, poorly sorted gravelly sands	3 m
Bølling	Top facies: fine to medium gravelly sands, gradual lithological changes	2–3 m
	lower facies: poorly sorted, medium to coarse sand and gravel, abrupt lithological changes	Not distinct
Pleniglacial	Poorly sorted, medium to coarse gravelly sand with grain size changing rapidly in vertical and horizontal direction	Mostly not distinct 0·5–1 m

area, on transect B–B' (Figures 1 and 5) and four in the northern part, partially on transect A–A' (Figures 1 and 5). Lithology, sedimentological structures and grain sizes are provided in Figure 6a and b.

Late Pleniglacial terrace sediments

The base of the terrace sediments varies from 5·9 m (boring LB, Figure 6a) to 7·5 m (boring WB, Figure 6a) below the terrace surface. In borehole LB a distinct change in lithology from coarse, gravelly, poorly sorted sand to predominantly fine-grained, well sorted sand with silt and clay layers marks the boundary between late Pleniglacial terrace sediments and older sediments. This is confirmed by the heavy mineral composition of samples lb32 and lb17 (Figure 6a, Table II) as sample lb17 matches the mineral composition of the late Pleniglacial terrace sediments (Huisink, 1997) with a high amount of stable and opaque minerals and a relatively low amount of hornblende and volcanic minerals, while sample lb 32 shows a higher amount of hornblende and volcanic minerals and a lower amount of stable minerals. In borehole WB the lithology changes in the hiatus between 7·4 and 8·4 m, at *c.* 8 m, where coarse-grained sands and gravels without calcium carbonate are replaced by clayey, fine-grained calcareous sands and gravels. The terrace sediments are, however, covered with 0·5 m of aeolian sands, so that the thickness of the fluvial terrace deposits is 7·5 m in borehole WB.

Bølling terrace sediments

The Bølling terrace sediments were deposited on top of the Late Pleniglacial river sediments. The change in fluvial style from the Pleniglacial to the Lateglacial did not involve the complete erosion of the braided river sediments but only reworking of the top sediments in the active floodplain of the transitional river system. The coarse sediments of the late Pleniglacial braided river and the lower facies of the transitional Bølling system cannot be distinguished (Table I; Huisink, 1997). The upper facies of the Bølling terrace (Table I) is therefore used to distinguish Bølling sediments from older deposits, which is at 5·9 m in borehole MH and at 6 m in borehole BW.

Boreholes HH and KH are located in channel scars and used to determine the depth of incision in the channels on this terrace surface by channel lag deposits. Near borehole HH (Figure 1), several small gullies merge in one large, curved channel (Vandenberghe *et al.*, 1994), which is typical for the transitional river system. The minimum depth of this channel is 5 m and is formed by a gravelly lag deposit. The thickness of Bølling sediments in borehole KH is most likely at 3·3m where a gravelly lag deposit is found. In order to estimate the total amount of erosion between the late Pleniglacial and

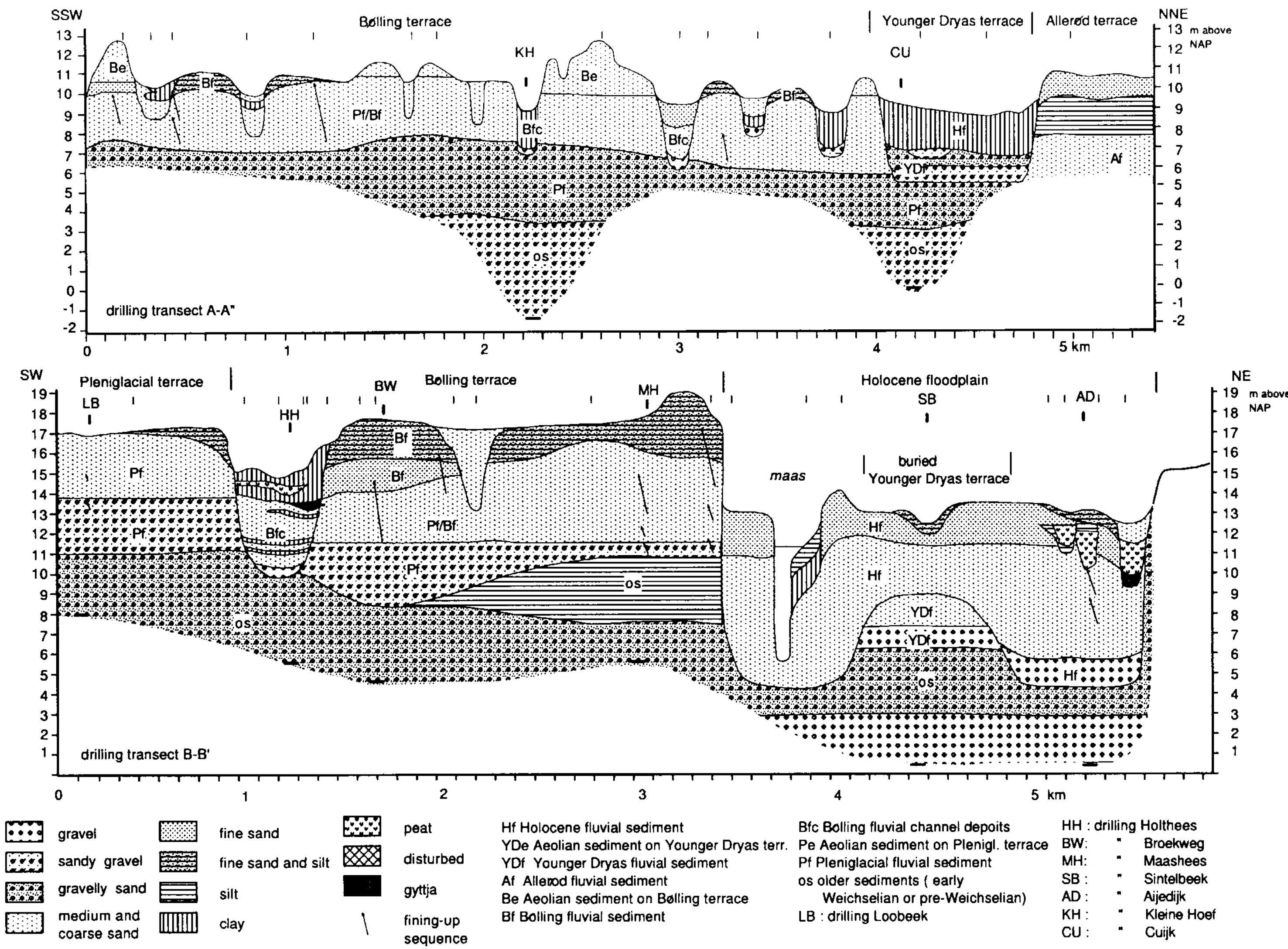

Figure 5. Borehole transects A–A' and B–B'; for location see Figure 1

Bølling, the depths of the channel fills in these boreholes have to be added to the altitude differences between the top of the channel fills and the terrace surface. This results in 7·1 m incision for borehole HH and 4·3 m for KH.

Allerød terrace sediments

The maximum depth of the meander scar south of borehole KO (Figure 1) is 5 m from the base of the channel fill to the top of the older terrace surface in which the channel has incised and the minimum thickness of the Allerød sediments is around 3·5 m (Kasse *et al.,* 1995). Further south a maximum of 7 m was found in another meander pointbar sequence (Kasse *et al.,* 1995), which is not used in these calculations since its position is outside the study area.

Younger Dryas terrace sediments

The Younger Dryas terrace sediments are found under Holocene sediments in the northern part of the area (boreholes CU and SB). The Younger Dryas sediments in borehole CU (Figure 6b) are found from 2 to 4·9 m below the surface, and are characterized by distinct short fining-up sequences and usually medium-grained sand ($< 600\,\mu m$). They contrast with the coarser underlying sand and gravel ($> 600\,\mu m$) without distinct fining-up sequences. The top 2 m of this borehole consists of fine-grained Holocene overbank deposits. In borehole SB the top 3·6 m consists of fine-grained, silty Holocene floodplain deposits. From 3·6 to 6·3 m Younger Dryas sediments occur as mostly coarse gravelly sand, separated from the underlying, also coarse sediments by a gravel lag deposit. Two heavy mineral samples from the Younger Dryas sediment at 4·6 m (sb20) and the underlying sediments at 7·5 m (sb34) show subtle differences. The amount of opaque minerals in sb20 (42 percent) points to a Younger Dryas sediment (Huisink, 1997), while sb34 contains somewhat high amounts of alterite, chloritoid and stable minerals and a lower amount of opaque minerals. The thickness of the Younger Dryas sediments is 2·87 m in boring CU and 2·63 m in boring SB.

Holocene floodplain deposits

Three boreholes were made in the Holocene floodplain (SB, AD and KO, (Figure 1), in which the depths of the Holocene sediments could be recognized by their mostly fine-grained nature or by their heavy mineral content. Hand borings were also used to estimate the thickness of the Holocene floodplain sediments because of the mostly fine-grained sediments which enabled a deep penetration. The maximum depth of the Holocene sediments is found in boring AD (Figure 6b), where at 7·4 m a gravel layer forms the coarse base of the Holocene deposits. An overall fining-up trend is seen, and most of the sediments are fine-grained, silty or humic. The maximum depth of about 7 m is observed in hand boreholes as well (Huisink, 1997). Two other mechanical borings, SB and KO (Figure 6b), show shallower depths. A gravel layer at 3·6 m in boring SB forms the boundary between the upper fine-grained Holocene deposits and somewhat coarser, gravelly Younger Dryas sediments which contain short fining-up sequences and a Younger Dryas heavy mineral composition (sample sb20 Figure 6b). The thickness of the Holocene deposits in KO (Figure 6b) is at least 3 m as fine-grained humic deposits like gyttja abruptly overlie a gravel layer which probably marks Holocene sedimentation after an erosional phase.

RESULTS: LATEGLACIAL REWORKING OF SEDIMENT

The combination of terrace sediment thickness and terrace dimensions is used to estimate the amounts of reworked sediment in each Lateglacial period. All calculations are based on the sediment that is stored nowadays in the Maas valley. The results are net erosional and depositional budgets and are used to

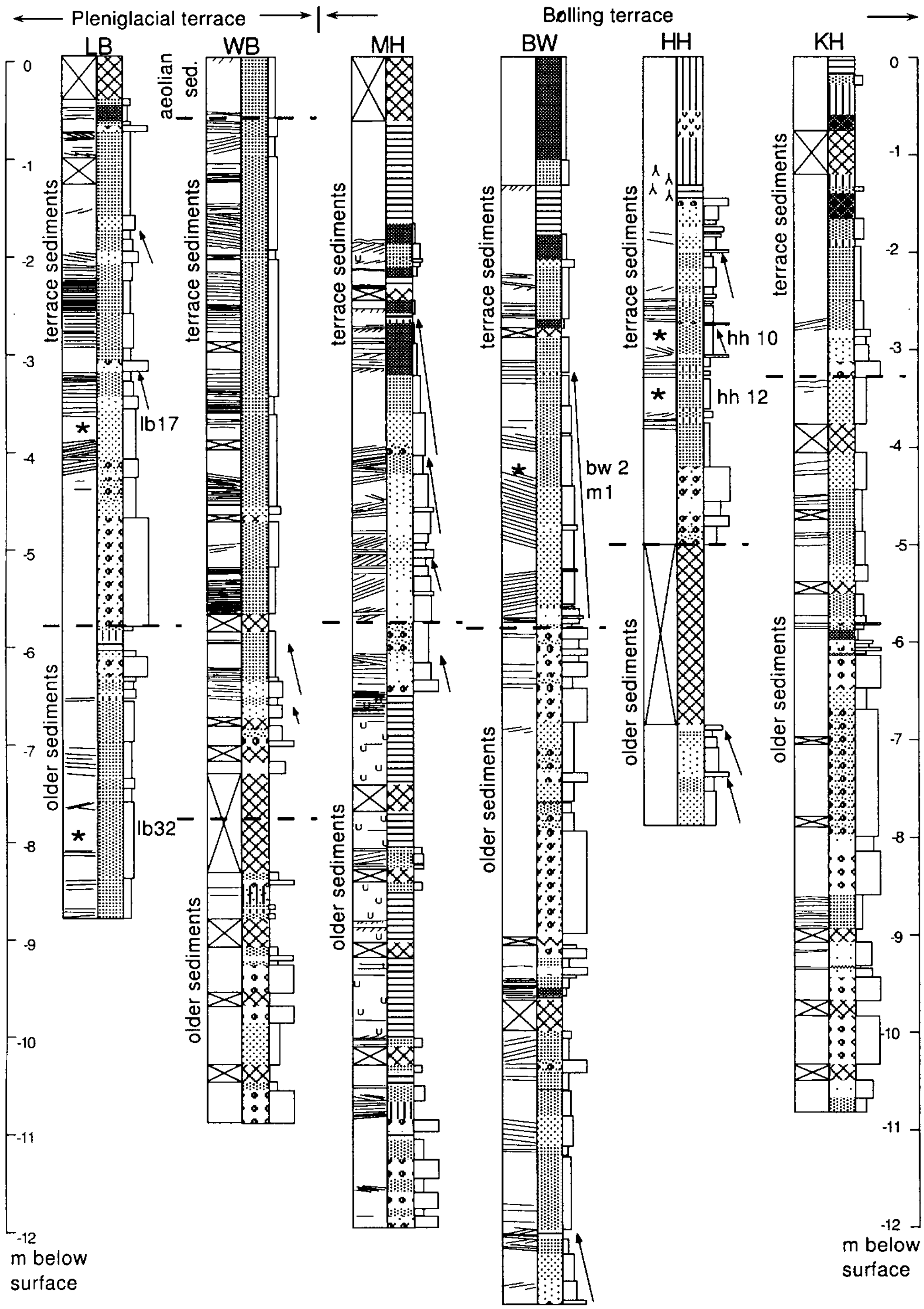

Figure 6 Borehole logs of (a) boreholes LB, WB, MH, BW, HH and KH and (b) boreholes CU, SB, AD and LO. For locations see Figure 1

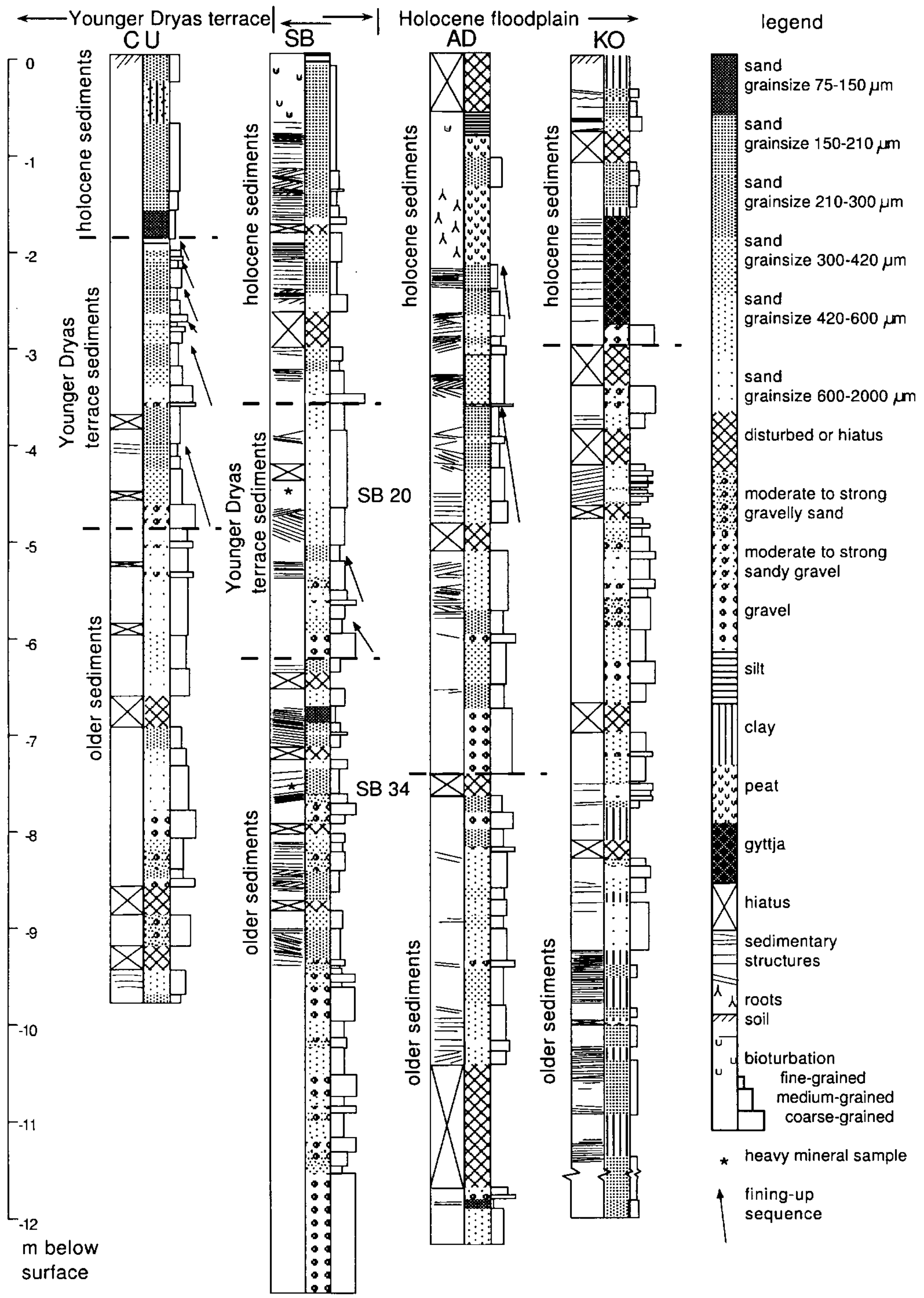
Younger Dryas terrace
Holocene floodplain
CU
SB
AD
KO
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
m below surface
holocene sediments
Younger Dryas terrace sediments
older sediments
SB 20
SB 34
legend
sand grainsize 75-150 μm
sand grainsize 150-210 μm
sand grainsize 210-300 μm
sand grainsize 300-420 μm
sand grainsize 420-600 μm
sand grainsize 600-2000 μm
disturbed or hiatus
moderate to strong gravelly sand
moderate to strong sandy gravel
gravel
silt
clay
peat
gyttja
hiatus
sedimentary structures
roots
soil
bioturbation
fine-grained
medium-grained
coarse-grained
heavy mineral sample
fining-up sequence

Table II. Heavy mineral content (percentage) of samples from boreholes. For locations see Figures 1 and 6

	lb17	lb32	bw2m1	hh10	hh12	sb20	sb34
Garnet	13·2	8·5	5·0	30·3	27·0	29·7	16·3
Epidote	8·8	9·0	25·7	12·4	14·0	19·3	15·3
Alterite + saussurite	6·9	7·0	8·4	4·5	3·0	5·0	15·8
Hornblende	5·4	10·0	2·5	2·5	3·0	1·0	0·5
Chloritoid	0	1·0	1·5	0	1·0	0·5	2·5
Volcanic minerals	2·9	9·5	2·0	1·5	3·5	2·0	0·5
Stable minerals	23·0	14·0	17·3	16·9	22·5	12·4	19·8
Unstable minerals	2·5	1·0	5·0	2·5	3·0	1·0	0
Topaz	0	0	1·0	0	0	0	0·5
Staurolite	9·3	10·5	10·9	7·0	4·5	10·9	10·4
Metamorphic minerals	8·8	11·5	5·9	7·0	7·0	4·0	2·0
Tourmaline	19·1	18·0	14·9	15·4	11·5	14·4	16·3
Opaque minerals	34	32	52	34	34	42	34

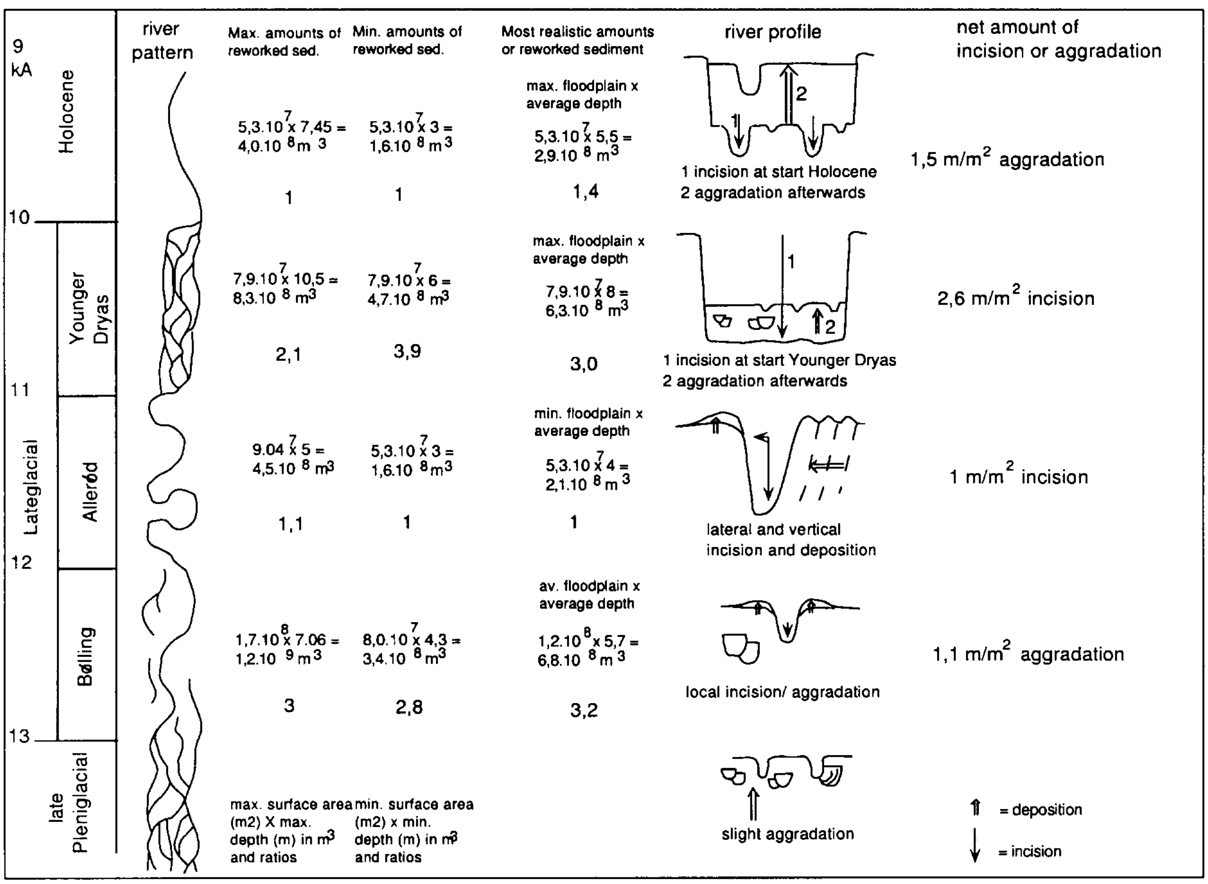

Figure 7. Synthesis of river pattern, reworked sediment and net incision or aggradation during the Lateglacial

compare Lateglacial fluvial changes. The amount of sediment transported through this part of the Maas valley during the Lateglacial is not estimated here. The maximum amount of reworked sediment is the maximum sediment depth multiplied by the maximum palaeofloodplain size and the minimum amount is the minimum depth multiplied by the minimum floodplain size (Figure 7).

The maximum amount of reworking in the Holocene (4×10^8 m^3) is comparable with that in the Allerød ($4{\cdot}5 \times 10^8$ m^3), but the reworking in the Younger Dryas ($8{\cdot}3 \times 10^8$ m^3) is twice as large and reworking in the Bølling ($1{\cdot}2 \times 10^9$ m^3) is three times as large. The minimum amounts of reworked sediment in the Holocene and Allerød are equal ($1{\cdot}6 \times 10^8$ m^3), while the amounts in the Bølling and Younger Dryas periods are considerably larger ($3{\cdot}4 \times 10^8$ m^3 and $4{\cdot}7 \times 10^8$m^3, respectively). In this scenario, the reworking in the Younger Dryas must have been larger than in the Bølling.

The average thickness is probably the most reliable value to use in the calculations, as the thickness of sediment bodies varies. The average thickness is combined with the average palaeofloodplain size for the Bølling, the minimum floodplain size for the Allerød and the maximum floodplain size for the Younger Dryas as these probably best represent the palaeo-floodplains. When the most realistic estimates of reworked sediment during the Lateglacial are compared (Figure 7), the smallest amounts of reworking occurred in the Allerød (21×10^8 m^3), 1·4 times as much in the Holocene ($2{\cdot}9 \times 10^8$ m^3), three times as much in the Younger Dryas ($6{\cdot}3 \times 10^8$ m^3) and 3·2 times as much in the Bølling ($6{\cdot}8 \times 10^8$ m^3).

Comparable amounts of reworked sediment are found for the Holocene and Allerød periods, while larger amounts are found in the Bølling and Younger Dryas periods. This is understandable since the river type during the Allerød and Holocene was meandering, while it was braided in the Younger Dryas and changing from braided to meandering during the Bølling. The amounts of reworked sediment in the Bølling and Younger Dryas are roughly the same, in spite of the differences in depths of incision between the Younger Dryas (up to 10·5 m) and the Bølling (6–7 m). The amount of reworked sediment in the Bølling and Younger Dryas periods is three to four times as much as in the Allerød which is explained by the more dynamic rivers transitional between braided and meandering and braided, respectively, during these periods, in contrast with a meandering river in the Allerød. Although the amounts of reworked sediment in the Holocene and Allerød are comparable, the dynamics of the two rivers were not comparable at all, since the Allerød lasted for 1000 years and the Holocene for 10 000 years. The dynamics of the Holocene river is therefore some 10 times lower.

NET EROSION AND DEPOSITION IN THE LATEGLACIAL

For each terrace surface (minimum, maximum and most likely) an elevation map was made. Net erosion and deposition between the terraces were estimated by subtracting elevation maps of subsequent terraces. Figure 7 shows the amounts of net erosion or deposition that were calculated by using the most likely terrace surface and the average sediment thickness. The minimum and maximum terrace surface areas were also used in the calculations to indicate the range in which the erosion or deposition occurred. Each grid cell had a higher or lower altitude after the subtraction. The overall altitude difference was estimated by adding up all grid cells of one terrace. This altitude difference was then divided by the total palaeofloodplain area to obtain the average sedimentation or incision per square metre.

The change from the braided late Pleniglacial river into a style transitional between braided and meandering in the Bølling resulted in net sedimentation. When the maximum and minimum possible Bølling palaeo-floodplain sizes are subtracted from the Pleniglacial floodplain the amount of sedimentation is 1·2 m m^{-2} for the maximum size and 1·1 m m^2 for the minimum size. The average floodplain size, which was considered the most likely floodplain size, results in a similar sedimentation.

The change from the Bølling to the Allerød is characterized by a change into one, meandering channel which eroded slightly. Four scenarios can be considered, namely the maximum or minimum Bølling surface being eroded by the maximum or minimum Allerød surfaces. All four calculations show erosion, ranging from 0·3 m m^2 (min. Bølling surface minus both the maximum and minimum Allerød surfaces) to 1·6 m m^2 (max. Bølling surface minus both the maximum and minimum Allerød surfaces). The

average of these amounts, around 1 m m^2 (Figure 7) is probably the most realistic amount of erosion, since the average of the maximum and minimum Bølling floodplain sizes is the most reliable palaeofloodplain size. Within the study area a difference is seen between the up- and downstream parts. For instance, when the maximum Bølling surface was eroded by the maximum Allerød surface 3·7 m sediment per grid cell was eroded in the most upstream part, whereas 0·9 m sediment per grid cell was deposited in the most downstream part. This demonstrates that fluvial processes are related to the position of the valley stretch examined. Rose (1995) demonstrated the complex fluvial responses of the River Gipping where aggradational and incisional phases changed from the steep uplands to the low-relief stretches.

The transition from the Allerød to the Younger Dryas period is marked by a deep incision on a floodplain scale (Huisink, 1997). The incision was partially filled with sediment during the Younger Dryas, but the net result is erosion, ranging from 2·6 (maximum Allerød surface eroded by the maximum Younger Dryas surface) to 2·9 m/m^{-2} (minimum Allerød surface eroded by the minimum Younger Dryas surface). The most likely scenario, where the minimum Allerød surface is eroded by the maximum Younger Dryas floodplain, cannot be calculated with accuracy but the range from 2·6 to 2·9 m m^{-2} erosion is quite satisfactory to indicate the possible amounts of eroded sediment. Erosion occurred in the whole study reach.

The change from the Lateglacial to the Holocene is marked by incision at first and sedimentation afterwards (Huisink, 1997), which filled the larger part of the Holocene floodplain. The most likely scenario, where the Holocene floodplain is subtracted from maximum Younger Dryas surface, shows an average sedimentation of 1·5 m m^{-2}. This is the amount of sedimentation on top of the Younger Dryas sediments. The incision at the start of the Holocene, however, was sufficient to erode most of the Younger Dryas sediments. The sedimentation during the Holocene was therefore much larger, at places up to 6–7 m (Huisink, 1997). So the net sedimentation calculated in this study is an underestimation.

Sedimentation rates, the average amount of sedimentation per year during each Lateglacial period, are not estimated as these are not reliable. Organic material is scarce in the Lateglacial Maas sediments which makes it difficult to define the duration time for each erosional and depositional phase. Another complicating factor is that the sediment stored in the Maas valley is the net result of each period. What happened within this period is hard to pinpoint in time. The sediment could have been aggraded during the whole period, but also during the last 100 years, which influences sedimentation rates greatly.

DISCUSSION

The Maas changed gradually from a braided river in the Late Pleniglacial via a transitional phase into a meandering river at the onset of the Lateglacial. The transitional river was thought to be active from around 12·7 ka until 11·8 ka BP (Kasse *et al.* 1995, Huisink 1997). However, according to Hoek (1997) the dates around 12·7 ka by Teunissen and De Man (1981) and Teunissen (1990) are some 500 years too old. A new date on macro-remains from organic detritus in the upper sandy facies of the braided river sediments in the Bosscherheide pit revealed an age of 12 390 + 100 years BP. This means that the Maas was still braided in the early Bølling, until *c.* 12·4 ka BP., although probably less dynamic than during the Late Pleniglacial. Afterwards the larger channels incised and became curved forming the multichannel transitional phase as described by Vandenberghe *et al.* (1994). Although the larger channels incised up to 7 m locally, a net aggradation occurred on a floodplain scale (see Figure 7). The first net incision on a regional scale occurred by the single-channel meandering river that was active from the late Bølling or early Allerød onwards.

The incision and change in fluvial style during the Bølling can be explained by changes in discharge – sediment ratios. The warming of the Lateglacial resulted in vegetation development from an open tundra into shrub tundra in the early Bølling, towards increasing amounts of birch copses in the Bølling *sensu stricto* and eventually into an open birch forest in the early Allerød (Hoek, 1997). This will have reduced slope erosion rates greatly (Kirkby, 1980) which resulted in prograding incision of the channels.

Discharges in the Bølling were highly irregular, related to snowmelt, because winter temperatures remained low in the Bølling period. As the soils were still frozen when snow began to melt in springtime, the soil water storage was low, and discharges would have had a peaked character. The result was a highly dynamic fluvial environment as is shown by the large amount of reworked sediment in this period (see Figure 7) which indicates a high eroding and transporting capacity. The vegetation development towards the end of the Bølling period resulted in a significantly reduced sediment load which led to incision on a regional scale. The vegetation development would have increased evapotranspiration rates as well which led to diminished discharges. The river became confined into a narrow floodplain in the Allerød when bank stability was high due to the dense vegetation cover.

This slow response to warming was quite different from the abrupt fluvial response to the Younger Dryas cooling. The Maas incised significantly on a regional scale most probably during the early Younger Dryas (Kasse *et al.,* 1995; Huisink, 1997) and changed its pattern towards braided without a transitional phase. Aggradation is thought to be active at least from 10 500 years BP onwards as aeolian dune accumulation occurred (Bohncke *et al.*, 1993) and the dune sand came from the palaeofloodplain (Huisink, 1997). The amounts of sediment that were reworked by the Younger Dryas braided river were comparable with those of the Bølling transitional river. Erosion occurred, however, in a different manner. Bed erosion took place in a confined, narrow floodplain and sedimentation afterwards was not enough to compensate for the erosion, while erosion in the Bølling period occurred in a wide palaeofloodplain, by shallow channels and erosion was balanced by sedimentation.

Discharges at the Allerød–Younger Dryas transition changed fast due to cooling and wetting of the climate (Bohncke *et al.,* 1987, 1993), becoming larger and more irregular. The vegetation, consisting of an open birch forest with pines (Hoek, 1997), formed a good protection against bank and soil erosion (Huisink, 1997) and remained intact at first. The increased discharge – sediment ratio resulted in erosion.

The vegetation changed during the Younger Dryas as the forest vegetation became more open from 10·95 BP onwards and the vegetation became less dense in the second half of the Younger Dryas (Hoek, 1997). This reduced bank and soil stability and increased sediment yields resulting in aggradation. The amounts of reworked sediment and the sediment itself in the Younger Dryas and Bølling periods are similar, which probably indicates that the stream power was comparable. The Younger Dryas river was, however, confined into a narrow floodplain and bank stability was higher due to the more dense vegetation cover. The excessive stream power was therefore spent on bed erosion, rather than lateral erosion, and the configuration of the Younger Dryas floodplain was thus determined largely by the confinement of the river into a narrow floodplain in the previous Allerød period.

The Maas incised at the onset of the Holocene warming and changed into a meandering river but, in contrast with the Bølling period, without a transitional phase. Incision took place at the very beginning of the Holocene, in the Preboreal (Kasse *et al.*, 1995) and probably dominated until accumulation became dominant in the Atlantic period (Berendsen *et al.,* 1995). In contrast to the onset of the Lateglacial, a dense birch wood vegetation quickly established (Hoek 1997), thereby reducing the sediment load. The rise of winter temperatures reduced the importance of snowmelt and discharges became more evenly distributed throughout the year. The fast changes in water and sediment supply accelerated the change in fluvial style.

Although a closed vegetation cover was present in the Allerød and Holocene, and in both periods the summer temperatures were high, a much higher amount of sediment was reworked during the Allerød period, namely five to 10 times more. This can be explained by the colder winter temperatures in the Allerød. The cold winters resulted in frozen soil in spring and thus in a low soil water retention capacity when discharges were high. The Allerød discharges were dependent mostly on snowmelt and were therefore strongly seasonal. This resulted in a high stream power and a highly dynamic meandering river that eroded, transported and deposited a large amount of sediment. Although the fluvial style of the Holocene and Allerød periods was similar, both being meandering, the Allerød river was much more dynamic and more comparable in stream power with the other Lateglacial river styles.

The Maas reacted to Lateglacial warming and cooling events by incision and changes in fluvial style.

This conforms to the model of Vandenberghe (1993, 1995) who proposed a non-linear response of a river to climate-related changes in water and sediment supply. These changes were significant enough to force the river to respond and to cross geomorphic thresholds (Schumm, 1977). Kozarski (1991) suggested a strong forcing of the vegetation cover on river development as changes in vegetation cover and river styles coincided in time. Rose (1995) explained Lateglacial channel changes of the River Gipping by changes in run-off and sediment supply (related to vegetation cover and soil development) but stressed the complexity of fluvial processes as these vary from up- to downstream parts of the catchment. Although only a small part of the floodplain is studied in this paper, changes between up- and downstream parts could already be observed. This is most evident in the calculated erosion of the Allerød period, when incision occurred in the upstream part, but deposition in the most downstream part.

The high amounts of reworked sediment during the Lateglacial show that these rivers were highly energetic, and had large stream powers which can be explained by the specific discharge characteristics. The low winter temperatures resulted in frozen soil at the time of snowmelt in spring, so soil water storage capacity remained low and discharges were highly irregular and peaked, resulting in a temporarily large stream power. The depth and rate of incision was strongly correlated with the vegetation cover development. The calculations in this paper showed that net incision on a regional scale occurred when a woody vegetation was present. Apart from external factors influencing the development of the Maas, an internal factor like configuration of the palaeofloodplain is thought to be important as well. The confinement of the Maas into a small floodplain in the Allerød resulted in the deep incision in the Younger Dryas period.

CONCLUSIONS

The Lateglacial warming resulted in diminished reworking of sediment from the late Pleniglacial to the Allerød and a change in fluvial style from braided via a transitional phase to meandering. During the Bølling, net sedimentation took place on a floodplain scale, regardless of incision of major channels on a local scale. Net incision occurred during the Allerød, by a meandering river, when sediment supply was relatively low due to a closed and woody vegetation cover. The cooling and wetting at the start of the Younger Dryas resulted in a change in fluvial style from meandering to braided. The amount of reworking became four times as much as in the previous period and net incision occurred. The change in pattern at the onset of the Holocene into a meandering river resulted in a much less dynamic river compared to the rivers in the Lateglacial. The amount of reworking in the Holocene is five to 10 times less than that of the meandering river in the Allerød and about 20 times less than during either the Younger Dryas or Bølling. These differences in river dynamics are related to the much more regular discharge regime and the complete cover of vegetation in the Holocene. This study shows that the Lateglacial configuration of the floodplain was strongly controlled by climate forcing (external factor), but also by the architecture of the floodplain in a previous period (internal factor).

ACKNOWLEDGEMENTS

This study was financed by NWO, Dutch Organization for Scientific Research and is incorporated in The Netherlands Center for Geo-Ecological Research (ICG). I thank Professor Dr J. Vandenberghe, Dr C. Kasse and Dr N. Asselman for their constructive comments on this paper and S. J. P. Bohncke for selecting the macro-remains for a new C14 date. I also thank the PCRaster research team, Faculty of Geographical Sciences, Utrecht University, The Netherlands, for permission to use the program and the support while working with PCRaster.

REFERENCES

Antoine, P. 1997. 'Modifications des systèmes fluviatiles à la transition Pléniglaciaire-Tardiglaciaire et à l'Holocène : l'exemple du bassin de la Somme (Nord de la France),' *Geographie physique et Quaternaire,* **51**, no.1, 93–106.

Berendsen, H., Hoek, W. and Schorn, E. 1995. 'Late Weichselian and Holocene channel changes of the rivers Rhine and Meuse in the Netherlands (Land van Maas en Waal),' in Frenzel, B. (Ed.), *European river activity and climate change during the Lateglacial and Holocene, Paläoklimaforschung,* **14**, 151–172.

Bohncke, S., Vandenberghe, J., Coope, R. and Reiling, R. 1987. 'Geomorphology and palaeoecology of the Mark valley (southern Netherlands): palaeoecology, palaeohydrology and climate during the Weichselian Late Glacial; *Boreas,* **16**, 69–85.

Bohncke, S. J. P. and Wijmstra, T. 1988. 'The Late-Glacial infill of three lake successions in the Netherlands: local vegetational succession and palaeohydrology', *Boreas,* **17**, 403–425.

Bohncke, S., Vandenberghe, J. and Huijzer, A. S. 1993. 'Periglacial palaeoenvironments during the Late Glacial in the Maas valley, The Netherlands', *Geologie en Mijnbouw,* **72**, 193–210.

Hoek, W. Z. 1997. *Palaeogeography of Lateglacial vegetations. Aspects of Lateglacial and Early Holocene vegetation, abiotic landscape, and climate in The Netherlands,* Thesis, Vrije Universiteit, Amsterdam, 147pp.

Huisink, M. 1997. 'Late Glacial sedimentological and morphological changes in a lowland river in response to climatic change: the Maas; The Netherlands; *Journal of Quaternary Sciences,* **12,** 209–223.

Huisink, M. 1998. 'Tectonic versus climatic controls on the River Maas dynamics during the Lateglacial.' in Benito, G., Baker, V. R. and Gregory, K. J. (Eds.), *Palaeohydrology and the Hydrological Science*, Wiley, Chicester, 99–109.

Isarin, R. F. B. 1997. Permafrost distribution and temperatures in Europe during the Younger Dryas, *Palaeogeography, Palaeoclimatology, Palaeoecology,* **8**, 313–333.

Jelgersma, S. 1966. 'Sea level changes in the last 10 000 years,' in: *International Symposium on World Climate from 8000 – 0 BC,* Royal Meteorological Society, 54–69.

Kalicki, T. and Zernickaya, V. P. 1995. 'Palaeogeography of the Vistula valley near Cracow based on sediments and palynology of the Allerød paleochannel fill,' in Starkel, L. (Ed.), *Evolution of the Vistula river valley during the last 15 000 years, Part V.* Geographical Studies, Special Issue, **8,** Polish Academy of Science, Wroclaw, 9–18.

Kasse, K. Vandenberghe, J. and Bohncke, S. 1995. 'Climatic change and fluvial dynamics of the Maas during the Late Weichselian and early Holocene,' in Frenzel, B. (Ed.), *European river activity and climate change during the Lateglacial and Holocene. Paläoklimaforschung,* **14,** 123–150.

Kirkby, M. J. 1980. 'The problem,' in Kirkby, M. J. and Morgan, R. P. C. (eds.), *Soil erosion*. Wiley, Chicester, 1–16.

Kozarski, S. 1983. 'The Holocene generation of paleomeanders in the Warta River valley, Great Polish Lowlands,' *Geologisches Jahrbuch Reihe A,* **71,** 109–118.

Kozarski, S. 1991. 'Warta – A case study of a lowland river,' in Starkel, L., Gregory, K. J. and Thornes, J. B. (Eds), *Temperate Palaeohydrology*. Wiley, Chicester, 189–215.

Lane, S. N. and Richards, K. S. 1997. 'Linking river channel form and process: time, space and causality revisited,' *Earth Surface Processes and Landforms,* **22,** 249–260.

Paus, A. 1995. 'The Late Weichselian and early Holocene history of tree birch in south Norway and the Bølling Betula time-lag in northwest Europe,' *Review of Palaeobotany and Palynology,* **85,** 243–262.

Pons, L. J. and Schelling, J. 1951. 'De laatglaciale afzettingen van de Rijn en de Maas,' *Geologie en Mijnbouw,* **13,** 293–297.

Rose, J. 1995. 'Lateglacial and early Holocene river activity in lowland Britain,' in Frenzel, B. (Ed.), *European river activity and climate change during the Lateglacial and Holocene, Paläoklimaforschung,* **14,** 51–74.

Schirmer, W. 1983. 'Die Talentwicklung an Main und Regnitz seit dem Hochwürm,' *Geologisches Jahrbuch Reihe A,* heft **71,** 11–43.

Schumm, S. A. 1977. *The Fluvial System,* Wiley, New York, 338 pp.

Teunissen, D. 1990. 'Palynologisch onderzoek in het oostelijk rivierengebied; een overzicht,' *Mededelingen Afdeling Biogeologi. Discipline Biologie Katholieke Universiteit Nijmegen,* **16**, 162pp.

Teunissen, D. and De Man, R. 1981. Enkele palynologische waarnemingen aan het kleidek van de Formatie van Kreftenheye bij Nijmegen. *Mededelingen Afdeling Biogeologi. Discipline Biologie Katholieke Universiteit Nijmegen,* **12,** 20 pp.

Vandenberghe, J. 1993. 'Changing fluvial processes under changing periglacial conditions,' *Zeitschrift für Geomorphologie N.F. Suppl. Bd.* **88,** 17–28.

Vandenberghe, J. 1995. 'Timescales, climate and river development,' *Quaternary Science Reviews,* **14,** 631–638.

Vandenberghe, J., Kasse, C., Bohncke, S. and Kozarski, S. 1994. 'Climate-related river activity at the Weichselian – Holocene transition: a comparative study of the Warta and Maas rivers,' *Terra Nova,* **6,** 476–485.

Van den Berg, M. W. 1994. 'Neotectonics of the Roer Valley rift system. Style and rate of crustal deformation inferred from syntectonic sedimentation,' *Geologie en Mijnbouw,* **73,** 143–156.

Van den Berg, M. W. 1996. *Fluvial sequences of the Maas. A 10 Ma record of neotectonics and climate change at various timescales,'* Thesis, University of Wageningen.

Van den Broek, J. M. M., and Maarleveld, G. C. 1963. 'The Late-Pleistocene terrace deposits of the Meuse,' *Mededelingen Geologische Stichting,* **16,** 13–24.

Van Geel, B., Coope, G. R. and Van der Hammen, T. 1989. 'Palaeoecology and stratigraphy of the Lateglacial type section at Usselo (The Netherlands),' *Review of palaeobotany and Palynology,* **60,** 25–129.

Veldkamp, A. and Van den Berg, M. W. 1993. 'Three-dimensional modeling of Quaternary fluvial dynamics in a climo-tectonic dependant system. A case study of the Maas record (Maastricht, The Netherlands),' *Global and planetary change,* **8,** 203–218.

Walker, M. J. C., Bohncke, S. J. P., Coope, G. R., O'Connell, M., Usinger, H. and Verbruggen, C. 1994. 'The Devensian/Weichselian Late-glacial in north-west Europe (Ireland, Britain, north Belgium, The Netherlands, northwest Germany),' *Journal of Quaternary Science,* **9,** 109–118.

Wesseling, C. G., Karssenberg, D. J., Burrough, P. A. and Van Deursen, W. P. A. 1996. 'Integrating dynamic environmental models in GIS: The development of a Dynamic Modeling language,' *Transactions in GIS,* **1,** 40–48.

